Developmental Science 9:1 (2006), pp F1–F12

FAST-TRACK REPORT

Two languages, one developing brain: event-related potentials to words in bilingual toddlers

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Abstract

Infant bilingualism offers a unique opportunity to study the relative effects of language experience and maturation on brain development, with each child serving as his or her own control. Event-related potentials (ERPs) to words were examined in 19- to 22-month-old English-Spanish bilingual toddlers. The children's dominant vs. nondominant languages elicited different patterns of neural activity in the lateral asymmetry of an early positive component (P100), and the latencies and distributions of ERP differences to known vs. unknown words from 200–400 and 400–600 ms. ERP effects also differed for 'high' and 'low' vocabulary groups based on total conceptual vocabulary *scores. The results indicate that the organization of language-relevant brain activity is linked to experience with language rather than brain maturation.*

Introduction

Recent studies have demonstrated that the experience of learning words shapes the organization of language-relevant neural systems in infants and toddlers independently of age (Mills, Coffey-Corina & Neville, 1993, 1997; Mills, Prat, Stager, Zangl, Neville & Werker, 2004; Mills, Plunkett, Prat & Schafer, 2005). To date, this literature has been limited to children acquiring a single language. Infants acquiring two languages simultaneously provide a naturally occurring test of the relative roles of maturation and experience. Functional imaging studies of bilingual adults have shown that the organization of language-relevant brain activity is influenced by complex interactions between language experience (proficiency and use) and age-related constraints on brain plasticity (for review see Abutalebi, Cappa & Perani, 2001); however, in retrospective studies of adults the relative influences of language experience and age on brain organization are difficult to assess because the two variables are often confounded. Prospective studies of infants growing up bilingually can help tease apart the relative roles of experience and maturational constraints on brain plasticity.

The goal of the present research was to investigate whether distinct processing systems for each language of bilingual toddlers are evident in the brain activity elicited by words in each language. Children raised bilingually typically have different levels of experience with each language (Pearson, Fernández, Lewedeg & Oller, 1997). In this research we recorded event-related potentials (ERPs) to known and unknown English and Spanish words in 19- to 22-month-old bilingual children to determine whether unequal levels of experience result in different patterns of brain activity for each language. We considered two possibilities. First, based on studies of bilingual primary language acquisition showing that each language develops along its own separate growth trajectory (for review see Meisel, 2001), we hypothesized that brain activity might be organized separately for English vs. Spanish according to the levels of experience in each. If separate neural systems mediated each language, ERPs to words would differ for each child's dominant vs. nondominant language. Second, based on studies indicating cross-language interactions during early bilingual development (e.g. Döpke, 2000; Gawlitzek-Maiwald & Tracy, 1996; Müller, 1998), we considered that a pooling of experience across languages could give

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rise to a general processing system mediating both languages, reflected in similar ERPs to words for each. If the same neural system mediated each language, ERPs to words would be similar across languages of the same children, and children with higher overall language ability would show different effects than children with lower overall ability. In either of these two scenarios, the ERPs would be expected to resemble those of monolingual children the same age and with the same approximate levels of either separate or overall language development (i.e. Mills *et al.*, 1993, 1997). However, we also considered that ERPs to words in bilingual toddlers could differ from those observed in monolingual children, reflecting specifically bilingual ways of language processing. Language processing in bilinguals varies along a continuum of bilingual to monolingual modes (Grosjean, 2001), and children raised bilingually have been shown to develop certain cognitive processes to a greater extent than those raised monolingually (Bialystok, 1999).

We specifically examined whether ERPs linked to known and unknown words in each language varied as a function of relative lexical development (vocabulary sizes in each language) and/or overall lexical-conceptual development (i.e. total conceptual vocabulary size, or TCV). In bilingual toddlers, TCV captures rapid gains in lexical development, known as the 'vocabulary spurt', better than single-language scores (Pearson, Fernández & Oller, 1993). Our predictions were based on previous research with monolingual toddlers in which specific components to known and unknown words varied with vocabulary size and the occurrence of the vocabulary spurt (reviewed in Mills *et al.*, 1993, 1997; Mills, Conboy & Paton, 2005). We hypothesized that differences in ERP known–unknown word effects for the dominant vs. nondominant language would provide evidence that the two languages are mediated by non-identical neural systems. In contrast, the lack of differences in ERP known–unknown word effects for the dominant vs. nondominant language would suggest that the two languages use a shared system. If differences in ERP known–unknown word effects were linked to TCV size but not to language dominance, this would be consistent with the view that such effects are related to language proficiency, but would also be consistent with a maturational viewpoint. That is, higher TCVs could result from brains that are more mature or are in some way better prepared to process language stimuli. In contrast, effects of both language dominance and TCV on the ERP patterns would support the role of experience in language development. The highest level of experience-driven proficiency would be demonstrated by the dominant language of the higher TCV group and the lowest level of experience-driven proficiency by the nondominant language of the lower TCV group.

Method

Participants

Participants were 30 19- to 22-month-old ($M = 20.3$ months) children (17 girls, 13 boys) whose first exposure to both English and Spanish occurred prior to 6 months of age. Participants were recruited from advertisements in parents' magazines, daycare centers and personal contacts. Parents signed consent forms approved by the University of California and San Diego State University Human Subjects Committees and received a small stipend for participating. Parent questionnaires were used to determine that participants had full-term, normal pregnancies and no history of hearing loss or language impairment. A parent language survey was used to assess exposure to each language (Conboy, 2002). All participants received at least 10 hours per week direct naturalistic exposure to each language. Exposure patterns ranged from having at least one person living in the home speak both languages to the child ($n = 20$); a 'one-parent, one-language' situation ($n = 3$); or exposure to one language through childcare and the other language in the home ($n = 7$). An additional 15 children were tested but excluded due to excessive artifact in the data.

Procedure

Language measures

Vocabulary size was measured using the English and Spanish versions of the MacArthur-Bates Communicative Development Inventories – Words and Sentences (Fenson, Dale, Reznick, Thal, Bates, Hartung, Pethick & Reilly, 1993; Jackson-Maldonado, Thal, Marchman, Bates & Gutiérrez-Clellen, 1993; Jackson-Maldonado, Thal, Marchman, Fenson, Newton & Conboy, 2003). Each form was completed within one week of ERP testing by the parent or caregiver who provided primary input in the relevant language. The number of translation equivalent pairs (e.g. 'water'-'agua') and English-Total and Spanish-Total vocabulary sizes were calculated based on the method described by Pearson *et al.* (1993) and a computerized scoring program (Marchman, 1999). TCV was determined by subtracting the number of times a translation equivalent pair occurred from the English-Total and Spanish-Total scores. Children were assigned to higher and lower vocabulary groups using a median split of the TCV scores. The TCVs ranged from 14 to 115 words ($M = 66.47$, $SD = 33.99$) in the lower group and from 122 to 458 ($M = 211.57$, $SD = 119.14$) in the higher group.

Each child's dominant language was determined using the English-Total and Spanish-Total scores and 3-point parent ratings for each language. On this scale parents

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judged whether their children's comprehension and use of each language was relatively low, medium or high (Conboy, 2002). Similar numbers of girls and boys were English-dominant (9 girls, 7 boys) and Spanish-dominant (8 girls, 6 boys).

Experimental stimuli

Individualized lists of 40 words (10 known and 10 unknown in each language) were determined within one week of ERP testing using a parent/caregiver rating scale. Caregivers indicated how sure they were that their child understood and/or produced each word on a scale of 1 (very sure the child did not know that word) to 4 (very sure the child understood/produced the word in a variety of different contexts and with different exemplars). The words included on this scale were early-acquired nouns selected from the English and Spanish CDI norming studies (Fenson *et al.*, 1993; Jackson-Maldonado *et al.*, 1993). A standard list was used whenever possible and additional words were substituted as needed, based on the caregiver ratings. Comprehension of known words was validated using a picture-pointing task. The unknown words in each language were low-frequency words matched for syllable structure with the known words. No two words on any child's list were cross-language synonyms.

All words were recorded in the same natural female bilingual voice using infant-directed speech. A two-way ANOVA indicated that Spanish words were longer than English words ($M = 924$ vs. 829.21, $F(1, 118) = 8.16$, $p < .01$) due to the higher prevalence of disyllabic words among early-acquired Spanish words. Within each language, known and unknown words were similar in duration. Each word was presented at an intensity level peaking between 64 and 77 dB SPL ($M = 69.85$). A two-way ANOVA confirmed no differences in intensity levels across languages or word types. Words were presented with a variable stimulus onset asynchrony ranging from 2400 to 4500 ms ($M = 3250$ ms) and variable inter-stimulus intervals of approximately 2000 ms. Each word was repeated five times, yielding 200 trials. The words on each list were pseudo-randomized in a mixed language order, with the same word never repeated twice in a row.

Electrophysiological testing

The electroencephalogram (EEG) was recorded using tin electrodes (Electro-Cap International) in a modified International 10–20 array (see Figure 1 for electrode placement). Results are reported for left and right frontal (F7/F8), anterior-temporal (50% of the distance from F7/F8 and T3/T4), temporal (33% of the distance from T3/T4 and C3/C4) and parietal (50% of the distance between T3/T4 and P3/P4) sites. Impedances were kept under 10 Kohms and balanced across left and right sites. The electro-occulogram was recorded from electrodes placed over (Fp1) and under the eye to detect vertical eye movements, and from left- and right-frontal electrodes to detect horizontal eye movements. All electrodes were referenced to linked mastoids.[1] The EEG was amplified at a gain of 20,000 by SA Instruments amplifiers with a bandpass of 0.1 to 100 Hz and sampled every 4 ms. The EEG was averaged using 2-second epochs, with a 100-ms pre-stimulus baseline. During testing, each child sat on the parent's lap in a sound-attenuated test booth and watched moving puppets while listening to the word stimuli from a speaker located 30 inches in front (see Mills *et al.*, 1993). Both languages were used during capping and testing in order to establish a 'bilingual mode' of processing (see Grosjean, 2001).

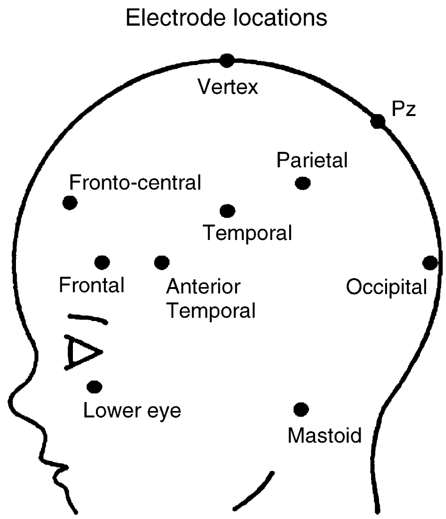

Figure 1 *Placement of electrodes in modified International 10–20 array: view from left hemisphere. Results are reported for: frontal (F7/F8); anterior-temporal (50% of the distance from F7/F8 and T3/T4); temporal (33% of the distance from T3/T4 and C3/C4); and parietal (50% of the distance between T3/T4 and P3/P4).*

[1] We are aware of the controversies surrounding the use of linked mastoids (i.e. Picton, Bentin, Berg, Donchin, Hillyard, Johnson, Miller, Ritter, Ruchkin, Rugg & Taylor, 2000). Linked mastoids were used here to increase the number of active sites given the number of amplifiers available and to provide consistency with previous studies. A pilot study using similar auditory stimuli was conducted to examine possible distortions in the distribution of scalp activity resulting from forced linkage. This was determined by recording from one mastoid, using the other as a reference, and linking the mastoids off-line. These pilot data were compared with the data recorded using linked mastoids and did not yield significant differences.

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ERP averaging and artifact rejection

Eye and muscle artifacts were identified off-line on a trial by trial basis through visual inspection and a computer program that detected blinks by measuring differences in the polarity of responses over and under the eye (see Mills *et al.*, 1993). Trials with eye movement and amplifier blocking were detected using thresholds set for each individual and removed prior to data averaging. Children for whom a minimum of 13 artifact-free trials per condition could not be obtained were excluded. There was an average of 28.71 usable trials for each word type in each language (range, 13–46).

Measurement of ERP components

The ERPs were averaged separately for known and unknown words in each language. Measurement windows for the P100 and later negative components were based on previous studies of monolingual children (Mills *et al.*, 1993, 1997), inspection of individual children's averages for each electrode site and grand averages. The P100 was defined as the most positive deflection between 50 and 180 ms, and measured using mean area and peak amplitude measurements. For the negative components, mean area measurements were taken between 200 and 400 ms (N200–400), 400–600 ms (N400–600) and 600–900 ms (N600–900). Area measurements were used due to variability in peak latencies.

Results

Each ERP measurement was analyzed in separate mixed-model ANOVAs with language (English vs. Spanish language for the first set of analyses, and dominant vs. nondominant language thereafter), word type (known vs. unknown), hemisphere and electrode site as within-subject factors. The between-subject factor was English-dominant vs. Spanish-dominant group or higher vs. lower TCV group, depending on the analysis. Greenhouse-Geisser corrections were applied when appropriate and partial eta-squared (η_p^2) was calculated for main effects and interactions. Planned comparisons were reported as significant at the .05 level and Cohen's *d* was calculated for effect sizes.

ERPs to English vs. Spanish words

Initial analyses were carried out on the P100 and N200–400 components to rule out effects of phonological differences between languages, using English vs. Spanish as the within-subject language factor and English-dominant vs. Spanish-dominant group as the between-subjects factor. First, we assessed whether the longer durations of Spanish words led to longer P100 peak latencies. Our prediction that differences in P100 latencies would be linked to language dominance rather than to whether the language processed was English or Spanish was supported: the P100 latency did not show significant differences between Spanish (M = 122.95, SD = 31.25) and English (M = 123.04, SD = 30.06). There was a main effect of English-dominant vs. Spanish-dominant group, $F(1, 28) = 10.26$, $p < .01$, $\eta_p^2 = .27$, indicating slightly longer latencies for the Spanish-dominant group. The interaction of English-dominant vs. Spanish-dominant group by English vs. Spanish language approached significance, $F(1, 28) = 3.85$, $p = .059$, $\eta_p^2 = .12$. The 14 Spanish-dominant children had slightly longer latencies to their nondominant language, English, than to Spanish words (133.79 vs. 128.27) and the 16 English-dominant children showed the opposite pattern (118.29 vs. 113.64), but the effect was not significant for either group.

Second, we assessed whether the N200–400 mean amplitude differed for English and Spanish words. There was no main effect of English vs. Spanish. However, for the Spanish-dominant group, the N200–400 amplitude was larger for Spanish vs. English known words, whereas the reverse was true for the English-dominant group, language by word type by site, $F(3, 84) = 3.16$, $p < .04$, and language by word type by site by group, $F(3, 84) = 3.69$, $p = .02$. A separate analysis of the nine children whose vocabulary scores were more 'balanced' (dominance quotients of .5–.6) yielded no significant main effects or interactions.

Based on these results, all further analyses were conducted using dominant vs. nondominant as the within-subjects language factor (Figures 2 and 3) and high vs. low TCV group as the between-subjects factor (Figure 4).

P100 peak amplitude asymmetries

In previous studies with monolingual toddlers the P100 was larger over the left than the right hemisphere over temporal and parietal regions for children scoring over the 50th percentile on the CDI, but not for children under the 35th percentile (Mills & Neville, 1997). We hypothesized that if the P100 asymmetry were linked to the rate of word learning, then in bilinguals it would be observed for the dominant but not the nondominant language. If the asymmetry were linked to brain maturation or a preparedness to process language in the left hemisphere, then the high TCV group would show a left asymmetry for both languages, regardless of language dominance, and the lower TCV group would not show it for either language.

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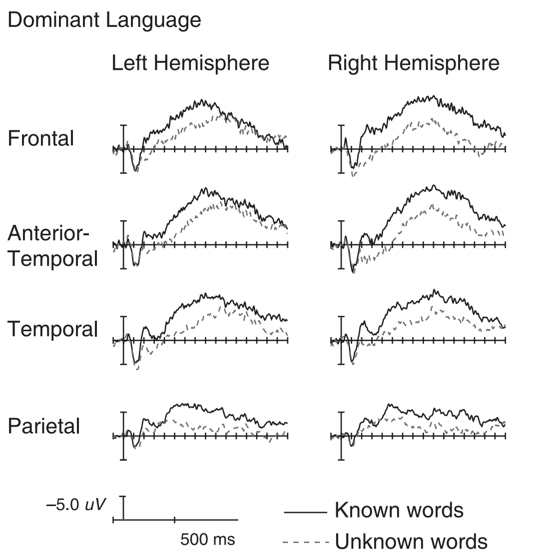

Figure 2 *ERPs to known and unknown words in the dominant language of all 30 children.*

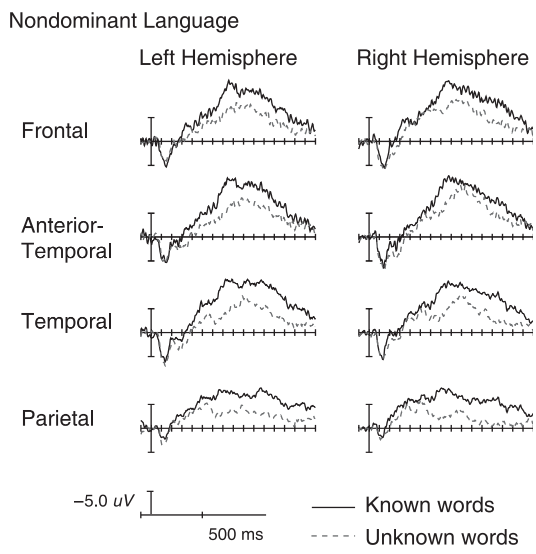

Figure 3 *ERPs to known and unknown words in the nondominant language of all 30 children.*

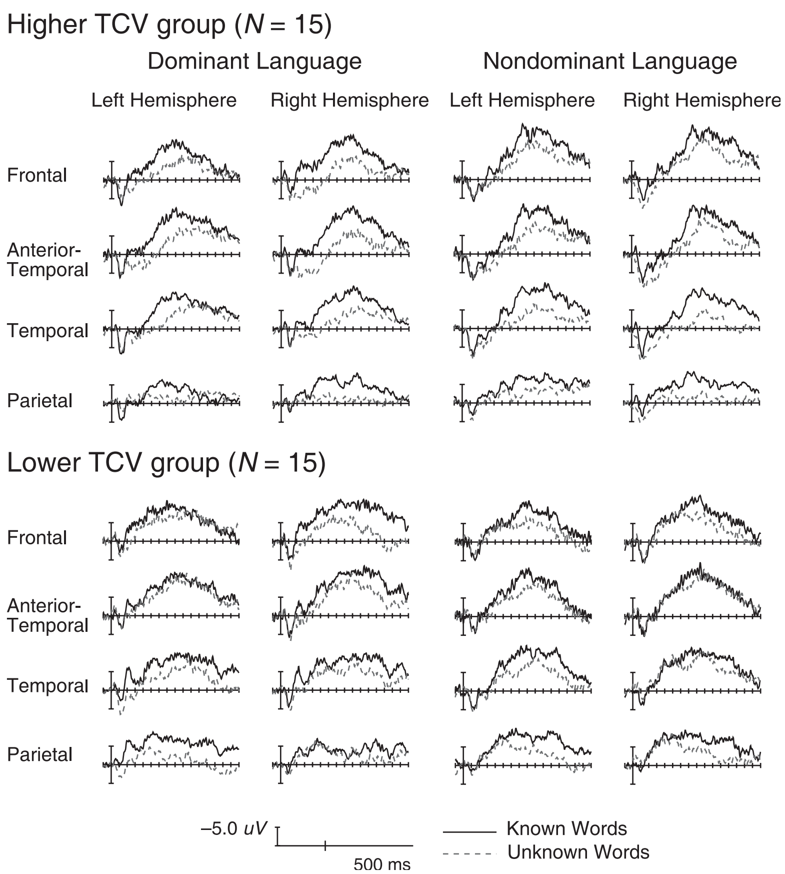

Figure 4 *ERPs to known and unknown words by TCV group.*

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All 30 children

The P100 amplitude did not significantly differ for the dominant vs. nondominant language. The predicted dominant vs. nondominant language by hemisphere by site interaction approached significance, $F(3, 28) = 2.53$, $p = .085$, $\eta_p^2 = .08$, and the hemisphere by word type by TCV group interaction reached significance, $F(1, 28) = 6.22$, $p < .05$, $\eta_p^2 = .18$. Consistent with our hypothesis, the P100 to known words in the dominant language was larger over left vs. right temporal and parietal sites; hemisphere at temporal, $F(1, 28) = 9.2$, $p < .01$, $d = .30$, hemisphere at parietal, $F(1, 28) = 5.36$, $p < .05$, $d = .27$. These asymmetries were not significant for the nondominant language. Planned comparisons were conducted for each TCV group since the monolingual studies indicated links between P100 asymmetries and vocabulary size.

Higher TCV group

The P100 to known words in the dominant language was larger over the left vs. right hemisphere at three sites: hemisphere at frontal, $F(1, 14) = 9.34$, $p < .01$, $d = .30$, temporal, $F(1, 14) = 16.02$, $p = .001$, $d = .41$, parietal, $F(1, 14) = 17.10$, $p < .001$, $d = .48$ (Figure 5). The left greater than right asymmetry was also significant for unknown words in the dominant language at temporal sites, $F(1, 14) = 5.44$, $p < .05$, $d = .33$. Thirteen out of the 15 high TCV children showed the asymmetry to known words at temporal and/or parietal sites. There was no significant asymmetry for the nondominant language.

Lower TCV group

There was no significant P100 asymmetry for either language.

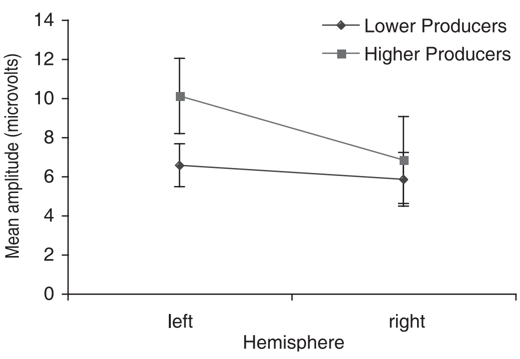

Figure 5 *P100 peak amplitude to known words in the dominant language (temporal sites).*

N200–400 known–unknown word amplitude differences

In our previous studies of monolingual toddlers, known words elicited more negative ERP amplitudes than unknown words from 200 to 400 ms, and there was a more focal distribution of the ERP differences in children with larger vocabulary sizes (Mills *et al.*, 1997). Based on these previous results, we predicted that in bilingual toddlers the N200–400 known–unknown word differences would be more focally distributed for children's dominant (higher-vocabulary) vs. nondominant (lower-vocabulary) language, and/or for children with higher vs. lower TCV sizes (i.e. pre- and post-spurt children).

All 30 children

Both known and unknown words elicited a negative response in this time window and ERP amplitudes were more negative to known than unknown words (Figures 2 and 3). For the entire sample the N200–400 was larger to known than unknown words, word type, $F(1, 28) = 5.53$, $p < .05$, $\eta_p^2 = .17$. A significant dominant vs. non-dominant language by word type by site interaction, $F(3, 84) = 3.39$, $p < .05$, $\eta_p^2 = .11$, indicated larger effects at anterior sites for the dominant language. The dominant vs. nondominant language by word type by hemisphere by site interaction approached significance, $F(3, 84) = 2.51$, $p = .08$, $\eta_p^2 = .08$. Because previous monolingual research indicated hemispheric differences in this effect, planned comparisons were conducted of known-minus-unknown word difference waves. These indicated that the N200–400 effects for the dominant language were larger over the right vs. left hemisphere at frontal, $F(1, 28) = 12.38$, $p < .01$, $d = .35$, and anterior-temporal sites, $F(1, 28) = 6.45$, $p < .05$, $d = .34$. There was no asymmetry for the nondominant language (Figure 6). Most children's ERPs discriminated between known and unknown words over at least one site (Table 1). Although there was no effect of TCV group, separate analyses were conducted for each group because previous studies of monolingual toddlers indicated that the distribution of the N200–400 effect varied with vocabulary size.

Higher TCV group

Planned comparisons at each electrode site indicated broadly distributed N200–400 effects for both languages. Comparisons of the size of the known-minus-unknown word difference waves indicated that for the dominant language only, the N200–400 effect was larger at right vs. left frontal sites, $F(1, 14) = 12.62$, $p < .01$, $d = .58$.

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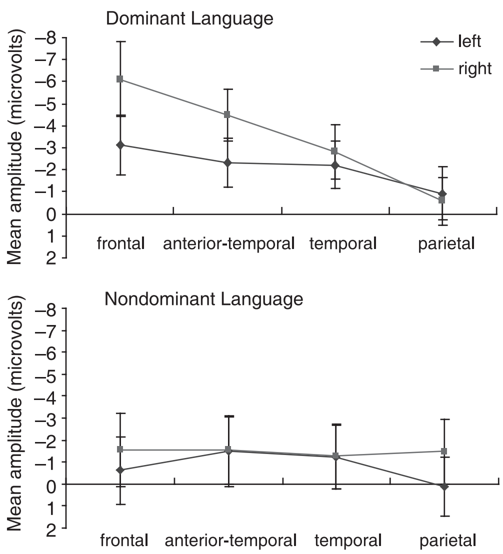

Figure 6 *Hemispheric differences in the N200–400 known–unknown word differences for all 30 children.*

Table 1 *Number of children[a] showing ERP amplitude differences to known–unknown words*

	Language	
Effect	Dominant	Nondominant
N200–400	28	24
N400–600	29	28
N600–900	28	26

[a] Children who showed the effect over at least one electrode site.

Lower TCV group

For the dominant language, known–unknown word differences were broadly distributed. Comparisons of difference waves indicated no asymmetries of the size of the effects. For the nondominant language the known–unknown word effect was not significant.

N400–600 known–unknown word amplitude differences

Based on adult studies indicating that ERP effects occur later in bilinguals we predicted that bilingual toddlers who did not show the N200–400 effect in their nondominant language (the lower TCV group) would show known–unknown word differences in a later window, from 400 to 600 ms.

All 30 children

The N400–600 effect was linked to both single-language vocabulary and TCV size. There was a significant dominant vs. nondominant language by word type by hemisphere by site interaction, $F(3, 84) = 3.87$, $p < .05$, $\eta_p^2 = .12$. For the dominant language the effects were broadly distributed at all eight left and right sites. For the nondominant language there were more limited differences, with a more frontal distribution for the left and a posterior distribution for the right hemisphere. Most children showed the effect over at least one site (Table 1).

Higher TCV group

For the dominant language, the N400–600 effect was broadly distributed at all left and right sites. Planned comparisons of difference waves indicated that the effect was larger over right vs. left frontal sites, $F(1, 14) = 7.01$, $p < .05$, $d = .46$. For the nondominant language the effects were broadly distributed with no asymmetry.

Lower TCV group

For the dominant language, the effects were broadly distributed, whereas for the nondominant language, the differences were significant only at the left temporal site. There were no lateral asymmetries in the size of this effect for either the dominant or nondominant language.

N600–900 known–unknown word amplitude differences

In monolingual toddlers known–unknown word differences were found in a later broad negativity (N600–900) over the right hemisphere at 13–17 months but not at 20 months. We predicted that in bilingual toddlers N600–900 known–unknown word differences would be significant for the nondominant but not the dominant language and for the lower but not the higher TCV group. We also predicted that the N600–900 to known words would be larger over the right vs. left hemisphere.

All 30 children

The N600–900 was larger to known than to unknown words, word type, $F(1, 28) = 13.73$, $p < .0001$, $\eta_p^2 = .33$. Contrary to our predictions, there were no main effects of dominant vs. nondominant language, hemisphere or higher vs. lower TCV group. A significant dominant vs. nondominant language by word type by hemisphere by site interaction, $F(3, 84) = 3.37$, $p < .05$, $\eta_p^2 = .11$, and planned comparisons at each electrode site indicated that the N600–900 effect was broadly distributed across all left and right hemisphere sites for both languages (Table 1). There were no asymmetries in the size of the N600–900.

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Higher TCV group

Planned comparisons indicated that for both languages the known–unknown word differences were significant at all left and right hemisphere sites. There were no hemispheric differences.

Lower TCV group

For the dominant language, the effects were significant at all sites except right parietal, and approached significance at left anterior-temporal. For the nondominant language, the effects were significant at all sites. The prediction that the N600–900 to known words would be larger over the right vs. left hemisphere was not supported for either group.

Discussion

The present study addressed two theoretical issues: (1) the distinctness of the brain systems mediating each language in toddlers raised bilingually, and (2) the role of experience in the development of language-relevant brain systems. The first question was motivated by adult studies showing that non-identical neural systems mediate each language when the second language is acquired after early childhood whereas the same brain systems mediate both languages when the second language is acquired in infancy or early childhood. The second question was motivated by studies of monolingual toddlers demonstrating the role of language experience in the development of language-relevant brain systems (Mills *et al.*, 1993, 1997, 2004), and is relevant to a recent functional imaging study of bilingual adults that shows that even in early bilinguals, there are differences in language-related brain activity linked to frequency of use of the language (Perani, Abutalebi, Paulesu, Brambati, Cappa & Fazio, 2003). In our prospective study of bilingual toddlers we asked whether the organization of language-relevant brain activity varied according to vocabulary size in each separate language (non-identical systems hypothesis) or was linked only to TCV size and not different for the dominant and nondominant languages (shared system hypothesis). The results showed that the organization of brain activity to words varied according to both separate-language vocabulary size and TCV size, suggesting an interaction between the two hypotheses.

Evidence that the two languages are processed by non-identical brain systems was observed in the timing of ERP differences to known vs. unknown words, which occurred earlier for the dominant than the nondominant language, and earlier for the higher than the lower TCV group. The high TCV group showed the N200–400 and N400–600 effects for both languages. In the low TCV group the N200–400 and N400–600 effects occurred only for the dominant language; for the nondominant language known–unknown word effects were not evident until much later, from 600 to 900 ms. ERP studies of bilingual adults have suggested three explanations for later processing of word meanings in one language than in the other. Longer latencies of semantic ERP effects have been reported for later- vs. early-acquired second languages (Neville, Mills & Lawson, 1992; Neville, Coffey, Lawson, Fischer, Emmorey & Bellugi, 1997; Weber-Fox and Neville, 1996, 2001); for the less proficient language within individuals (Ardal, Donald, Meuter, Muldrew & Luce, 1990; Moreno, Federmeier & Kutas, 2002; Moreno & Kutas, 2005); for both languages of bilinguals compared to monolinguals (Ardal *et al.*, 1990); and when bilinguals switch between languages (Moreno *et al.*, 2002). In the present study ERP latency differences due to age of acquisition can be ruled out, since all participants began exposure to both languages well before the onset of word learning. Switching between Spanish and English during testing in this study may have had an effect on processing by creating a greater cognitive load for the nondominant language in children with smaller TCV sizes. However, a pilot study in which 10 bilingual 20-month-olds were tested on the same paradigm, but in four blocks of 50 English and Spanish words rather than in a mixed language condition, suggested otherwise. When the results of that group were compared with those of a subset of children from the present study matched for TCV and separate vocabulary sizes, the latency of known–unknown word effects was similar across groups (Conboy, 2002). The most likely explanation for our present results is that latency differences were linked to experiential differences between the dominant and nondominant languages. These results may indicate a speed of processing effect that interacts with language ability. For children who are slower in overall language development, processing is slower in the nondominant language but not affected in the dominant language.

Evidence that the two languages are processed by non-identical brain systems was also observed in the distribution of ERP effects. Across the entire sample, ERP known-unknown word differences were observed over both hemispheres. However, for the higher TCV group these effects were *larger* over right vs. left anterior sites for the dominant language, and symmetrical for the nondominant language. Consistent with previous studies of monolingual toddlers, a more focally distributed pattern of ERP differences was linked to a larger vocabulary size

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in the dominant vs. nondominant language. Our pilot study with children tested in a blocked condition suggests that the language switching design used in the present study may have contributed to the right over left asymmetries at frontal/anterior-temporal sites. Studies with bilingual adults have likewise suggested that language switching recruits tissue in frontal areas (Hernández, Martinez & Kohnert, 2000; Hernández, Dapretto, Mazziotta & Bookheimer, 2001; Jackson, Swainson, Cunnington & Jackson, 2001; Price, Green & von Studnitz, 1999). However, it remains unclear why switching during testing would result in asymmetries only for the dominant language of the higher TCV group. Additional research is needed to determine whether these right-anterior lateral asymmetries in bilinguals are affected by the mode of testing.

There are several differences between these data and the previous monolingual findings. Monolingual 20-month-olds showed N200–400 known–unknown word differences only over temporal and parietal regions of the left hemisphere (Table 2), and did not show these effects in the later N600–900. In the present study, even the children in the high TCV group showed N200–400 and N600–900 effects over both hemispheres. These patterns are more similar to those observed in 13–17-month-old monolingual children and 20-month-old late-talkers, and may be due to the smaller vocabulary sizes of these three groups (see Mills, Conboy *et al.*, 2005). When the vocabulary sizes of each of the bilingual toddlers' languages were considered separately, they more closely resembled those of younger monolingual children, as reported for other bilingual children this age (Pearson *et al.*, 1993). They also more closely resembled the vocabulary sizes of 20-month-old monolingual late-talkers (Mills, Conboy *et al.*, 2005). A recent ERP training study showed that the distribution of N200–400 differences to newly trained vs. untrained novel words was linked to both vocabulary size and experience with individual words (Mills, Plunkett *et al.*, 2005). The bilingual children in this study, like younger monolinguals and 20-month-old late-talkers, may have had less experience or practice with the known words in their nondominant than dominant language, even though the picture-pointing task and parent reports indicated that they comprehended all of the known words they were tested on.

The different distributions of the N200–400 and N400–600 ERP effects across monolingual and bilingual children may reflect resource allocation for dealing with two languages. Studies of bilingual adults have suggested that early bilinguals show greater right lateralization for the second language than late bilinguals (Paradis, 1990; Vaid & Hall, 1991). Thus the right hemisphere might be involved in simultaneous bilingual acquisition more so than in monolingual or successive bilingual acquisition.

The N600–900 effects in the bilingual children in this study, monolingual 13–17-month-old lower comprehenders

Table 2 *Comparison of ERP effects across bilingual and monolingual studies*

	Bilingual children (19–22 mos.)				Monolingual children		
	Lower TCV		Higher TCV		13–17 mos.		20 mos.
Effect	DOM	NDOM	DOM	NDOM	Lower group	Higher group	All
N200–400[a]							
Left	F, T, P AT~	*ns*	F, AT	AT, T	All sites	F, AT, T, P	T, P
Right	F, AT, T	*ns*	F, AT, T P~	All sites	All sites	F, AT, T	*ns*
N600–900[b]							
Left	F, T, P AT~	All sites	All sites	All sites	F, AT, T	*ns*	*ns*
Right	F, AT, T	All sites	All sites	All sites	F, AT, T	*ns*	*ns*
P100 L > R asymmetry	*ns*	*ns*	F, T, P	F~	*ns*	T, P[c]	T, P

Note: DOM = Dominant language, NDOM = Nondominant language; F = frontal, AT = anterior temporal, T = temporal, P = parietal; TCV = Total conceptual vocabulary size. Effects reported if significant at $p < .05$ unless otherwise noted.
[a] The ERP components shown to vary with word type in the studies of monolingual children (Mills *et al.*, 1993, 1997) were the N200 and N350. In the present study the differences in the 200–400-ms range were reported; for the sake of comparison across studies, the results of both the N200 and N350 for monolingual children are combined here.
[b] ERP known–unknown word differences were measured in a 600–1200 ms window in the 13–17-month-old monolingual children studied by Mills *et al.* (1997).
[c] For the monolingual 13–17-month-olds the P100 asymmetry was found in infants whose CDI-WS scores were over the 50th percentile (higher group).
~ Trend ($p < .10$).

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and 20-month-old late-talkers are similar in timing and distribution to those of the Nc component reported in other studies of infants, which indexes attention and integration of stimuli (Courchesne, 1978; Karrer & Ackles, 1987; Nelson, 1994). Thus the N600–900 effect may reflect the need for enhanced attention during known word processing. It is possible that the unique demands of bilingualism require such enhanced attention. However, it is also noteworthy that the words in the present study were recorded in infant-directed speech and thus were longer in duration than those used in the previous studies of monolingual toddlers in which adult-directed speech was used, and this could have led to longer processing times.

The results of this study support the hypothesis that differences in both individual and overall language experience interact to shape the organization of language-relevant neural systems in bilinguals. Different patterns of activity were observed for the dominant and nondominant languages even in very young bilinguals. The results also have theoretical implications for the development of cerebral specialization and lateralizations for language. Previous studies of monolingual children showed that the P100 to known words was larger over the left than the right hemisphere for children scoring over the 50th percentile for their age, independent of chronological age or absolute vocabulary size, whereas it was symmetrical in children scoring below the 35th percentile (Mills *et al.*, 1997) (see Table 2). In light of these and more recent data we have hypothesized that the lateral asymmetry of the P100 is linked to faster rates of learning, whereas the lack of this asymmetry is linked to more slow and effortful processing (Mills, Conboy *et al.*, 2005). An alternative explanation is that the left greater than right asymmetry in the higher vocabulary groups is due to faster brain maturation or an initial preparedness to process speech in the left hemisphere, and that the presence of a left greater than right asymmetry leads to better language skills. In the present study, the higher TCV group showed a left greater than right P100 asymmetry to known words for their dominant language, and no asymmetry for the nondominant language (Table 2). We suggest that the focalized, left asymmetry for the P100 to known words in the dominant language of higher producers reflects the use of a more efficient, automatized processing system for that language. The asymmetry cannot be due to differences in brain maturation or a preparedness to process speech in the left hemisphere because differences linked to experience were found within the same developing brains.

Finally, it is important to note that the ERP differences to known vs. unknown words were not due to phonological differences between English and Spanish. Differences in the latency of the P100 and amplitudes of the N200–400 varied according to language dominance rather than English vs. Spanish. The amplitude of the N200–400 was similar to known words in English and Spanish, and to unknown words in English and in Spanish. That is, even when there were strong phonological differences, the amplitude of the N200–400 was modulated by word meaning, not phonology.

Conclusions

ERP results from infants being raised with two languages provide strong evidence that the process of learning language shapes the organization of language-relevant brain activity. Differences in the timing and distribution of brain activity linked to word meaning differed for children's dominant vs. nondominant language. These findings cannot be attributed to differences in rates of brain maturation nor genetic factors because the effects of experience were observed in the same developing brains. The comparisons between bilingual and monolingual children also suggest that a bilingual learning environment may give rise to patterns of neural activity that are qualitatively different from those found in monolingual development. Finally, these results raise questions about the interpretation of adult findings related to age of acquisition in that similar patterns for dominant vs. nondominant languages were observed in infants acquiring both languages at the same time. The results suggest that language proficiency and experience should be considered in studies of bilingual individuals of any age.

Acknowledgements

This research was supported by grants to Barbara Conboy from Head Start (Administration on Children and Families), National Institute of Mental Health (University of California, San Diego training grant), the University of California Linguistic Minority Research Institute, and by a grant to Helen Neville from the National Institute on Deafness and Communication Disorders NIH 5 R01-DC0048111. We thank Renate Zangl, Chantel Prat, Terra Llamas, Eric Fritz and Mark Rojas for assistance with data collection, Marie St George for assistance with data analysis and Patricia Kuhl, Maritza Rivera-Gaxiola and Juan Silva-Pereyra for comments on earlier versions of the manuscript. We also thank Donna Thal and Elizabeth Bates for helpful discussions on this topic. We are especially indebted to the children and parents who participated in the studies. This study was based on a doctoral dissertation by Barbara T. Conboy.

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Received: 1 September 2005
Accepted: 7 October 2005

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